ON-ORBIT OPERATING EXPERIENCE WITH THE NICMOS CRYOCOOLER—FIRST YEAR

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ABSTRACT

A mechanical cryocooler was installed on the Hubble Space Telescope (HST) in March 2002. The turbo-Brayton cooler uses miniature high-speed rotors in gas bearings to provide vibration-free refrigeration. It is designed to re-cool the detectors on the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The cryocooler system has been operating continuously since March 19, 2002. In May 2002, the setpoint temperature was set to provide a detector temperature of 77.1 K. Detector temperatures have been maintained within ± 0.1 K by a control loop that continually adjusts compressor speed around a nominal value of 426,600 rpm. An important feature of the turbo-Brayton cryocooler is its exclusive use of self-acting gas bearings to support the miniature, low mass rotors. This approach results in extremely low vibration levels and wear-free operation. When combined with suitable decontamination procedures, the resulting hermetic system can be contamination free, resulting in un-degraded operation for periods of 5–10 years. This paper reviews the first year on-orbit operating experience with the NICMOS cryocooler and presents additional laboratory results with a version of the system ultimately designed for cooling at 6 K.

BACKGROUND

The NICMOS was installed in January 1997 during Servicing Mission 2 to the HST. Because of a thermal short in the NICMOS cryostat, the solid nitrogen that was used to cool the detectors was subliming at an accelerated rate resulting in an expected useful life of about two years rather than the three plus years originally intended. NASA approved an experimental solution to the loss of cooling in July 1997 by initiating a program to develop and install a mechanical cooling system on the HST. The NICMOS Cooling System (NCS) would interface with the NICMOS cryostat through existing vacuum-jacketed bayonet fittings that had been used in ground operations to supply cold helium for cooling the nitrogen in the cryostat.

Several factors influenced the system design. The system had to have the potential for successful operation for five years. It had to be able to provide sufficient refrigeration to restore the useful resolution of the detectors at about 77 K, yet heat loads were only approximately known. Temperature stability was to be maintained within +/- 0.1 K with significant variations in thermal environment (because of orbital heat flux and changes in pointing attitude). EMI and EMC requirements for the HST had to be met, and vibration and jitter were critical. Finally, the system had to be packaged for EVA installation.

The system was designed, fabricated, and ground-tested during the next 12 months. In October 1998, the NCS was space qualified during the Hubble Orbital System Test that included ten days of nearly continuous operation on STS-95. Following the qualification flight, the system was refurbished to improve several of the system components. Additional ground tests were conducted to establish the final performance figures for the system, address control issues, and to assess vibration characteristics of the system. Nitrogen in the NICMOS cryostat was fully depleted in January 1999.

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Creare had been developing cryocooler technology for about 20 years prior to the NICMOS launch. One particular system had been developed to the engineering model level and had been operating in a life test for about three years. It produced 5 W of refrigeration at 65 K using a reverse Brayton refrigeration cycle. A key feature of the system was that it employs turbomachines with small, very high-speed rotors operating in gas bearings. These machines have excellent life characteristics, and are inherently low vibration because of the precision low mass rotors. The 5 W, 65 K cooler uses 215 W of input power and was an attractive candidate for the cryocooler portion of the NCS.

Nominal operating requirements were established for the NCS. They are listed in Table 1. Creare used thermodynamic models of the existing 65 K cryocooler to define the design for the NCS system. Because the system was to be installed on orbit, it was decided to use two separate loops for the cryocooler portion of the system. A hermetically sealed cryocooler would serve as the main heat pump. This was supplemented by a cryogenic circulating loop that would interface with the NICMOS dewar. In this way, the risk of neon loss over time could be minimized and controlled. The cryocooler would be launched with its neon inventory intact. The circulator loop would be launched empty and filled on orbit after connecting to the NICMOS dewar. Excess neon would be stored in supplemental tanks that could be activated to replenish the circulator loop if there was leakage at the tube interfaces.

Table 1: *Nominal operating parameters for the NICMOS Cooling System (NCS)*

Parameter	**Value**
Detector Temperature	77.1 K +/- 0.1 K
Cryostat Dome Temperature	~ 72.4 K
Cryostat Parasitic Heat Load	~ 400 mW
Neon Temperature at NICMOS Inlet	~ 65 K
Temperature at NCC Heat Rejection Interface	~ 278 K
Total Refrigeration Power	7.1 W
Radiator Temperature	- 28°C to - 10°C
NCS Power Consumption	~ 375 W

The addition of the circulator (between 0.5 and 1 W of heat at the cold end) and other interfacing characteristics resulted in an estimated cryocooler refrigeration requirement of about 7 W. This and limitations imposed by packaging raised the compressor input power from 215 W in the engineering model version to about 375 W in the NCS configuration. The hardware for the NCS was only a mild extension of technology that had already been developed and demonstrated. However, all components required space qualification.

COOLER DESCRIPTION

The NCS consists of three independent fluid loops shown in Figure 1: a cryogenic circulation loop, a closed loop cryocooler, and a capillary pumped loop. In the circulator loop, a small 72,000 rpm centrifugal circulator conveys neon at a continuous flow rate of about 0.4 g/s through tubing between the NICMOS cryostat and the cold load interface at the cold end of the cryocooler. The heat from NICMOS is rejected at the cold load interface through a series of small finned passages in a heat exchanger. In the cryocooler, a small centrifugal compressor operating at 400,000–430,000 rpm compresses neon to a pressure ratio of about 1.7. The heat of compression is rejected to the capillary pumped loop at the heat rejection interface. The neon flows through a recuperative, counterflow heat exchanger where it is cooled by a return stream from the cold end of the cryocooler. The gas expands through a turbine at the cold end removing heat from the fluid and dissipating it through an alternator at a resistive load in the electronic controller. The turbine operates at 150,000–270,000 rpm with a refrigeration capacity of 7–15 W. Temperature control and refrigeration capacity is adjusted by changes to the compressor speed, thus increasing or decreasing the turbine output. The cooled gas exiting from the turbine absorbs heat in the cold load interface and then is heated in the low-pressure side of the recuperator as it returns to the compressor inlet. Flow is steady and continuous at about 1.7 g/s in this loop. The capillary pumped loop uses ammonia that vaporizes at the heat rejection interface. At the radiator, the vapor condenses and the liquid flows back to the heat rejection interface by capillary action.

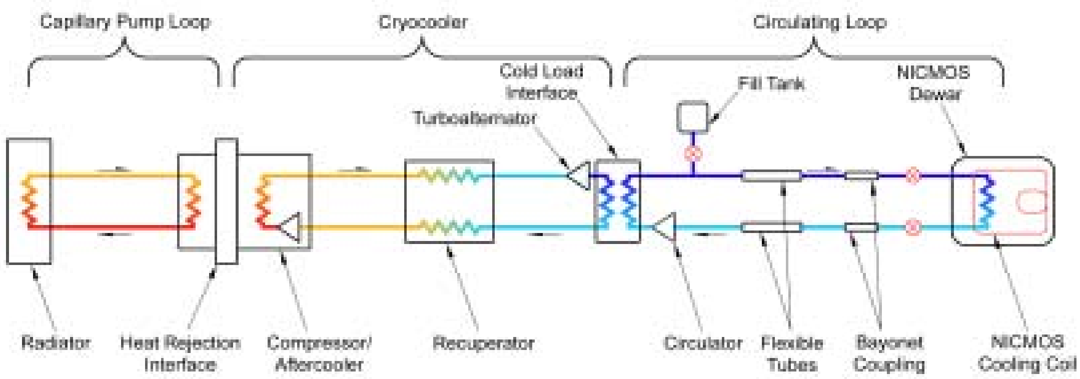

***Figure 1**: NICMOS Cooling System Schematic.*

The three subsystems are packaged for on-orbit EVA installation. Figure 2 shows the cryocooler and circulator loop during integration. The compressor is fastened to the back plate at the bottom of the assembly. The recuperator is the tubular component with a vertical axis between the bottom of the package to the top. The cold load interface is at the top of the recuperator and supports the two cold end turbomachines—the circulator (foreground) and the turboalternator (hidden). Cold end sensor leads are staked to the exterior surface of the recuperator shell. The electronics package including a DC/AC adjustable frequency inverter, the circulator drive and instrumentation electronics mount above the compressor on the back plate. The frame provides support for the cryocooler, pressure transducers, neon fill and replenishment tanks, electronics, and the heat rejection interface connecting to the capillary pumped loop. The frame footprint is about 0.5 m x 0.5 m.

Rigid tubing at the top of the frame connects to the cold load interface. Flexible tubes (approximately 1 m long) are welded to the rigid tube ends. The flexible tubes have modified bayonet ends that interface with the bayonet fittings on the NICMOS support panel.

Following the installation of the electronics, the entire cold end is wrapped in multi-layer insulation to reduce radiation heat loads. Side panels are added to prevent damage to the assembly during handling and EVA.

***Figure 2**: Cryocooler during integration.*

ON-ORBIT OPERATION

The cooldown started in mid-March, 2002. During the first 25 days, the cryocooler removed heat from the large NICMOS cryostat at a rate of about 10 W. When the control temperature reached 70 K, the machine was set to maintain that temperature. Figure 3 shows a time plot of several temperature sensors at the cold end of the system. NICMOS Outlet and NICMOS Inlet temperature sensors are attached to the tubes on the NCC assembly. NICMOS Inlet therefore is the coldest fluid exiting the cold load interface and entering the flexible tube to NICMOS. NICMOS Outlet is located just upstream of the inlet to the circulator. The difference between these two temperatures is approximately proportional to the heat load absorbed in the tubes and the NICMOS cryostat. Turbine inlet temperature is measured on the cold load interface and is only a rough approximation of the actual fluid temperature at the inlet to the machine. Control temperature is a calculated figure designed to approximately estimate the temperature at the detector cold bench in the NICMOS assembly. The approximation was derived from tests on a NICMOS simulator at GSFC.

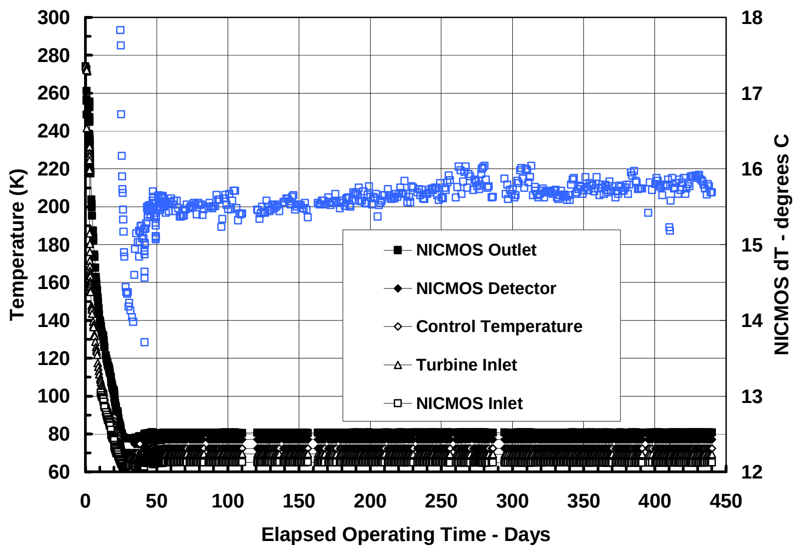

Figure 3. *Operating data since cooldown.*

Following the initial cooldown, the control temperature was adjusted in steps to evaluate system control response and to assess the behavior of the detectors. The control temperature was then set in order to maintain the detectors at 77.1 K. The five temperatures shown in Figure 3 are identified in the order of their value. They have remained within operating limits since the control temperature was initially set. The heat load to the circulator loop is indicated by the temperature difference between NICMOS inlet and outlet (NICMOS dT). These data indicate a small increase in heat load to the cryocooler from day 50 to present. Some of this change may be a result of the periodic change in solar flux during the year. Short period variations are due to changes in the aft shroud thermal environment primarily resulting from pointing attitude and orbit.

LOWER TEMPERATURE SYSTEMS

The operating history of the NCS has verified the reliability and attractive features of this type cooling system. Present efforts focus on extending this technology to lower temperatures and lower refrigeration capacities. This involves improved fabrication methods to further reduce the size of the basic cryocooler components. A development effort is currently underway through the Cross Enterprise Technology Development Program to produce a turbo-Brayton cooler suitable for up to 100 mW of refrigeration in the 6 K–10 K range. Two smaller compressors have been on life test in a cryogenic facility with a cold end temperature at 20 K since December 2002 supporting this effort. A subminiature turboalternator will be tested later this year in a cryogenic closed loop performance test.